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PHILOSOPHICAL BASIS FOR RISK ANALYSIS

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INTRODUCTION

All societies and individuals have recognized exposure to personal risk as a normal aspect of our life. Presumably such risk exposures have been accepted as necessary to attain a compensating benefit. This relationship has been explored previously, and several hypotheses have been suggested to explain the historically accepted balances of risk and benefit (1, 2).

When individuals have "voluntarily" taken risks for personal pleasure or profit, they appear to be willing to accept relatively high risk levels in return for rather modest quantifiable benefits. For example, sportsmen frequently explore the outer physical limits of their chosen activity—with many resultant statistical accident records of their risk-taking propensities. Assuming that intangible benefits do exist, the controlling parameter appears to be the individual's perception of his own ability to manage the risk-creating situation. If he believes he can do so, he is likely to take the chance.

The situation changes markedly when the individual no longer believes he can control his risk exposure. In such "involuntary" situations, the risk management is in the hands of a societal group usually remote operationally from the individual and his risk exposure. Major societal technical systems all create such involuntary risk exposures—for example, transportation systems, energy supply systems, public utilities, and food supply systems. Whereas in the voluntary case the feedback loop of "control of risk–benefit balance" is very tightly coupled by the individual, in the involuntary case this loop is usually very weakly coupled, dimly perceived, and with each of its elements usually dispersed in time, geographically, politically, and managerially. Under these circumstances, the individual exposed to an involuntary risk is fearful of the consequences, makes risk aversion his goal, and therefore demands a level for such involuntary risk exposure as much as one thousand times less than would be acceptable on a voluntary basis (1, 2).

Inherent in all operational major technical systems is an implicit choice of such an acceptable level of risk for the involuntary exposure of the public. The study reported in (1, 2) has suggested the hypothesized relation shown in Figure 1 between

risk and benefit as a typical basis for such decisions. The figure shows the approximate relation between the per capita benefits to real income of a system and the acceptable risk as expressed in deaths per unit time (i.e. time of exposure in units of a year). The highest level of acceptable risks that may be regarded as a reference level is determined by the normal US death rate from disease (about 1 death/year per 100 people). The lowest level for reference is set by the risk of death from natural events—lightning, flood, earthquakes, insect and snake bites, etc (about 1 death/year per 1,000,000 people).

Between these two bounds, the public is apparently willing to accept involuntary exposures—i.e. risks imposed by societal systems and not easily modified by the individual—in relation to the benefits derived from the operations of such societal systems.

In common familiar terms, an involuntary risk may be considered *excessive* if it exceeds the incidence rate of disease, *high* if it approaches the rate, *moderate* if the risk is about 10–100 times less, *low* if it approaches the level of natural hazards, and *negligible* if it is below this. Events in these last two levels of risk have historically been treated as acts of God by the public generally—in recognition of their relatively minor impact on our societal welfare compared with the effort required to avoid the risk.

Thus any risk created by a new sociotechnical system is acceptably "safe enough" if the resultant risk level is below the curve of the figure. If, as is usually the case, a new technical system has a range of uncertainty in its risks, a design target may

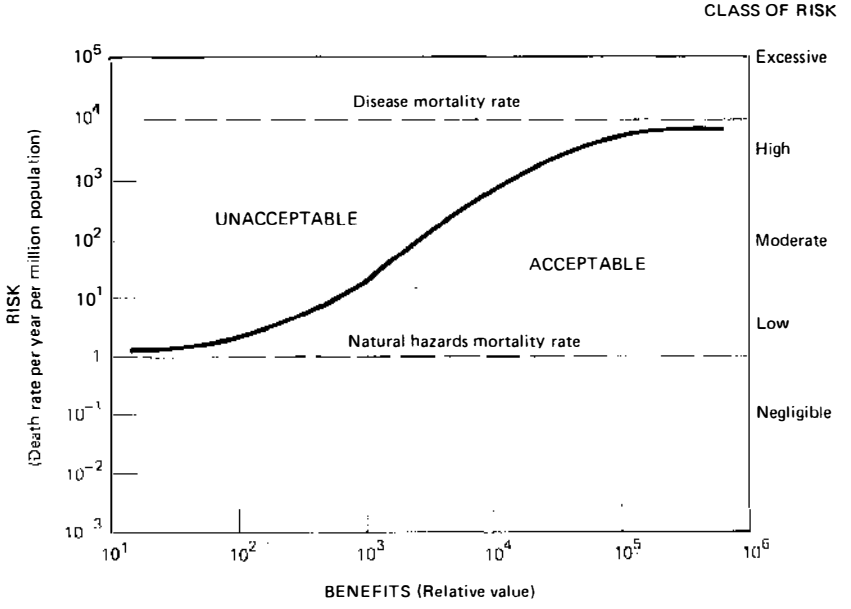

Figure 1 Benefit-risk pattern of involuntary exposure.

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be set below the curve by an equivalent amount—possibly as much as a factor of 10 or 100.

Although the relationship hypothesized in Figure 1 appears reasonable, its quantitative aspects should be considered as very tentative and primarily useful for illustrative purposes. The evaluation of the comparative benefits derived from the availability of technical systems is complex, difficult, and presently more heuristic than analytic. Because most new technical systems initially appear to be replacements for existing systems (for example, nuclear for coal power), public policy is generally concerned with comparative risk levels rather than comparative benefits. Perhaps it is not usually foreseen that new technology is likely to affect societal systems profoundly—the automobile became more than a substitute for the horse, although it was originally perceived only as a horseless carriage.

Thus, because comparative risk analysis is the issue of primary national concern, this chapter focuses its discussion on the risk portion of the risk-benefit balance.

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EVALUATION OF RISK

The study of risk analysis has as its objective the development of a methodology for predictive evaluation of future risks. Unfortunately, the literature on "futures" is apt to be obfuscated by a mix of personal value-system assessments of present trends and imaginative scenarios of alternative futures, usually written to dramatize the author's bias. For this reason it is useful to recognize the existence of four different evaluations of future risk, as follows:

1. *real risk,* as will be determined eventually by future circumstances when they develop fully;
2. *statistical risk,* as determined by currently available data, typically as measured actuarially for insurance premium purposes;
3. *predicted risk,* as predicted analytically from system models structured from historical studies; and
4. *perceived risk,* as seen intuitively by individuals.

Air transportation illustrates the above types of risks. To the flight insurance company, flying constitutes a statistically known risk; to the passenger purchasing the insurance at the airport, a perceived risk. In this case the perceived risk usually exceeds the statistical risk.[1] To the Federal Aviation Administration, anticipated changes in air traffic patterns and equipment involves predicted risk as an approximation to future real risk.

Perception

In some cases, the risk that an assessor predicts by careful analysis of experimental and historical data, the use of scientific laws, transfer of experience from related

[1] The rate for life insurance at airports is $0.25 per $7500 insurance per flight. By 1971 data, this rate is approximately 30 times the actuarially fair value. Regular life insurance is usually available at somewhat less than twice the actuarially fair rate.

data, or a combination of these methods does not correlate well with either an individual or a societal perception of risk. Perhaps the single most important factor in risk perception is risk manageability or controllability, where an individual feels safer if given some control over the degree of risk from an activity. Examples of this may be found in transportation where individuals perceive more risk from flying than driving, or in skiing, when an individual expresses more fear riding a chair lift up a mountain than skiing down. In both cases, the perception is not borne out by accident statistics. This is possibly the significant issue that results in voluntary activities having acceptable levels of risk several orders of magnitude higher than the levels associated with involuntary activities (1). It is usually difficult to differentiate between a faulty perception of risk and its distortion by a personal value system that results in a preference for a statistically higher risk, even when the risks are known, as in sports.

An important factor in the perception of risk is the probable severity of injury if an accident were to occur. A complete assessment of risk requires that the potential effects of an accident be combined with a probability of occurrence. Because the accident probabilities are usually not given significant weight in an individual perception, concentration on accident consequences can lead to distortions of perception. Again the perceived safety of commercial air transportation suffers relative to the automobile (although the real risk is less) because the results of an average aviation accident are far more severe than the effects of the average automobile accident. Similarly, motorcycling is perceived as far more dangerous than automobile travel because of this perceptual factor. In this case, the perception is accurate, as accident statistics reveal that motorcycle riders are exposed to a greater risk than automobile passengers.

Another very significant factor is the episodic nature of some risks. On an individual level, a risk is usually perceived as a probability of death, with less severe effects such as disability, either temporary or permanent, considered insignificant in comparison to the risk of fatalities. On a societal level, the episodic preoccupation is evident in the common concern with disasters claiming many lives, while in fact single-fatality accidents are responsible for the majority of all accidental deaths. It thus seems that the size of the potential accident is given more weight than the probability. This factor dominates the popular perception of risk from nuclear power plants, and can be recognized when the criticisms of nuclear power are examined, as the potential results of a major accident are frequently cited with no mention of the associated probabilities. This is probably representative of societal values to a great degree, and activities capable of producing catastrophic accidents therefore must meet more stringent societal standards than higher-frequency, individual risks. The failure to consider probability is, however, a perceptual factor.

One time-dependent effect that occurs in risk perception is the discounting of future risk. The risks of smoking would seem far less acceptable if the risk were experienced immediately, rather than developed over a number of years. This perception does not seem to apply when nuclear power is discussed, probably because of the dramatic scenarios that have been developed for hypothetical nuclear accidents. Because the principal health effect of low-level radiation exposure is

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increased likelihood of cancer in the future, occurring perhaps 15 to 45 years after exposure, this risk should also be discounted. In most adversarial discussions of nuclear power, these are treated as immediate fatalities.

Perception of Benefit

Just as risk may be perceived to be different from the assessed value, so too may societal perceptions of benefit vary. In a previous paper (1), an attempt was made to relate risk data to a crude measure of public awareness of the associated social benefits (see Figure 2). The "benefit awareness" was arbitrarily defined as the product of the relative level of advertising, the square of the percentage of population involved in the activity, and the relative usefulness (or importance) of the activity to the individual. These assumptions may be too crude, but Figure 2 does support the reasonable position that advertising the benefits of an activity increases the public acceptance of a greater level of risk. Smoking has been cited as an example of a perceived benefit due in large part to advertising (3). The decision to ban cigarette advertising on television indicates a tacit understanding of this phenomena.

Perception versus Reality

When a gap appears between the perceived and assessed risks and benefits, the societal decision-makers are called upon to resolve the conflict. A recent example of such a resolution was the requirement that automobiles be equipped with a seat belt interlock system. In this case, the individual perception underestimated the risk, as the majority of people were not using seat belts. The regulatory decision was made that the reduction in risk was substantial enough to justify the

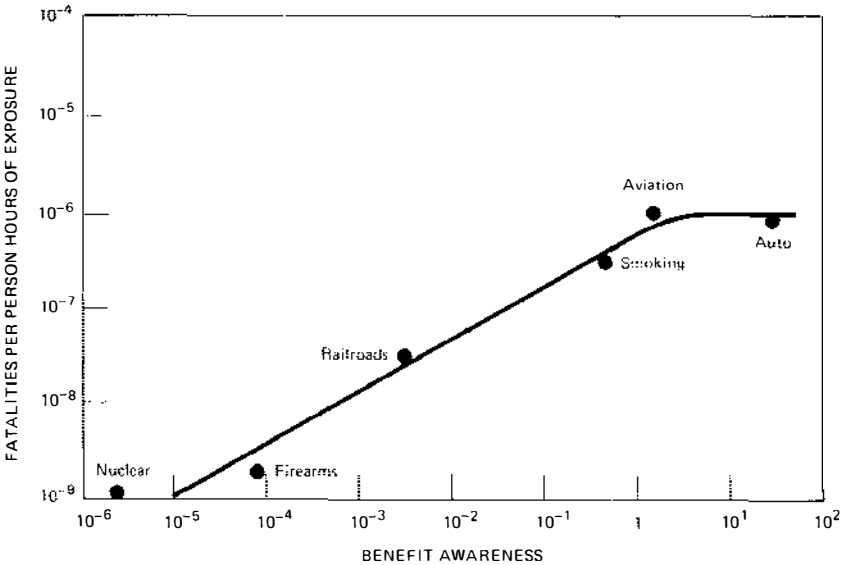

Figure 2 Accepted risk versus benefit awareness.

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cost of the safety system. This regulation was subsequently repealed because the total social cost of the system was underestimated, that is, the cost of inconvenience was apparently significantly large.

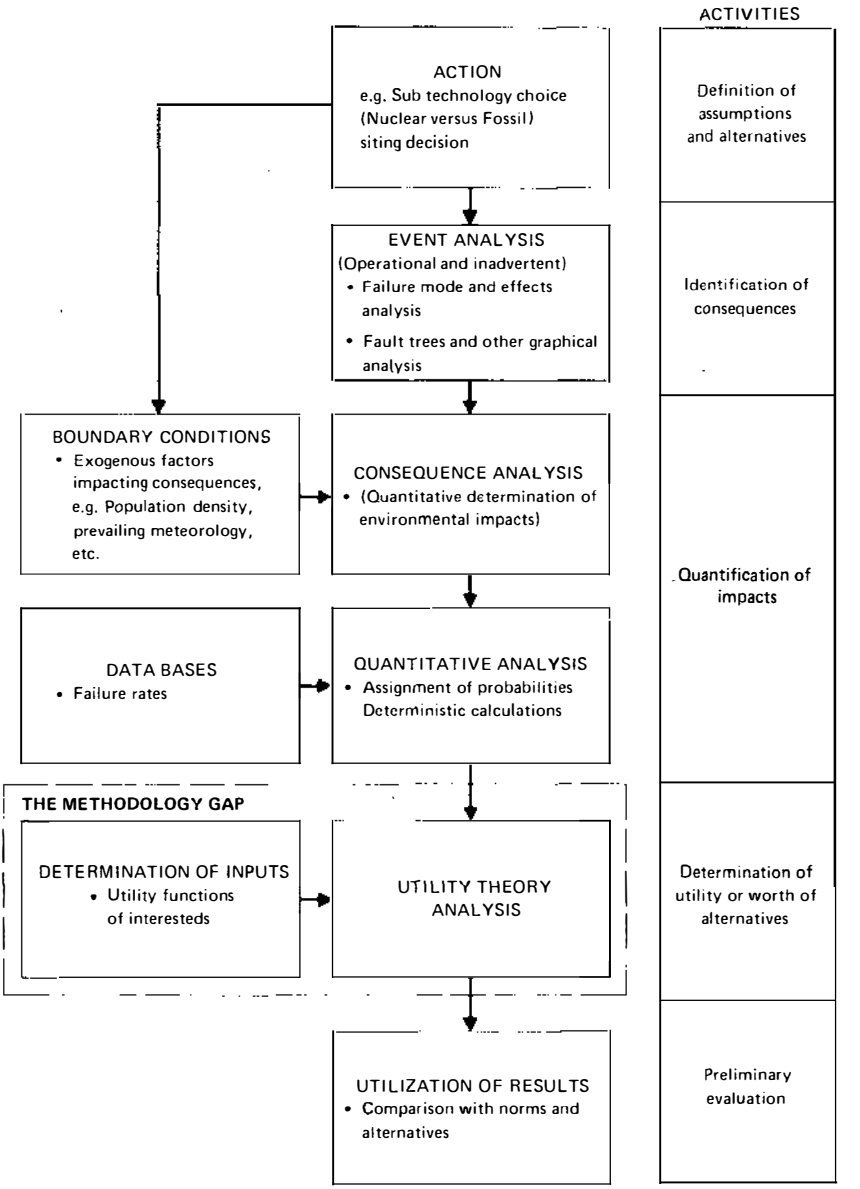

Figure 3 Illustrative flow chart: risk analysis. Source: (4).

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No general method of dealing with differences between perception and technical assessment exists in the societal decision-making process. This problem is not directly within the realm of the technologist, as the technologist is not generally the decision-maker. The role of the technologist is to provide an assessment of risk and benefits. The societal perceptions and values are made visible through normal political inputs. The technologist should, however, indicate to the decision-maker that reliance on societal perceptions will usually result in a misallocation of resources. The difficult task of separating faulty perceptions from societal values has not been resolved.

Situations frequently arise where the individual member of society simply does not have the information to relate perception to reality. As a case in point, we may consider the perception of the solar system. To those who are not astronomers, the visible evidence is that the sun travels around the earth. The only reason that the population as a whole believes otherwise is that the word of the scientists has become part of the common wisdom. What seems significant about this situation is the duration of the perceptual lag, that is, the time between scientific discovery and cultural acceptance.

Three levels of perceptual problems can be identified. First, there are the real-time problems of perception. These include the factors previously identified as controllability, episodic preoccupation, and other similar effects. The second problem is perceptual lag. In general, perception eventually catches up with reality, but the time required may result in a massive misallocation of resources in the interim. The third level of perceptual problem is assessment of hypothetical future risks. If decisions were based entirely upon public perception, many technologies would not exist now because an exaggerated fear of new risks would have prohibited their introduction.

Societal Value System for Risk

The incorporation of risk estimates into national decision-making is in its early stages of methodological development. The use of a societal value system for risk acceptance must rank as the major unresolved issue in this part of the decision process. While methods have been proposed (4), none has yet been put into practice. Figure 3, taken from (4), is representative of a proposed method of dealing with this issue.

In the past, and to a lesser extent at present, the scientific community has tended to view risk-taking decisions based on factors other than the expected value of the risk as irrational. Because society responds to more factors than just expected value, a conflict has arisen. An outgrowth of this conflict has been that groups concerned or threatened by risk have rejected the estimates developed by the risk analysts. In seeking an input to the decision-making process, these groups have challenged the estimated risk, because on intuitive grounds the risk seemed less acceptable than the expected value would indicate. The need to consider these public perceptions is clear.

Although the source of conflict may be recognized, the resolution of the societal decision-making process is by no means simple. The societal value system fluctuates

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with time, and the technological capability to follow fast-changing societal goals does not exist. As an example, the emission requirements for automobiles were established at a time when air quality was considered far more important than fuel economy or cost. The societal goals in this area have seemingly changed to some degree, as these two latter considerations are now given more weight.

This fluctuation of social values makes the decision process more difficult and serves as perhaps the strongest argument for analytic decisions. Resolving the gap between societal perception and analytically expected value is of prime importance and requires a balanced consideration of both concepts. The aim of such a process is to maintain consistency within the framework of a value system.

The particular method referred to in Figure 3 is called *utility theory*; briefly stated, its estimates measure the social values associated with various objectives on a common scale. In theory, the diverse social costs associated with energy production, and with a lack of energy, may be estimated for comparison. The key question in such a method is that of estimating a societal utility function. This process occurs in a nonempirical manner at present. The social value system is made known through various channels of public expression such as elections, letters to congressmen, and the many polls. Such a process is incapable of separating values from perceptions.

Use of Risk Data

A decision-maker is frequently called upon to compare different types of risk (and more generally, different types of social cost) resulting from any of the various options under consideration.

At one end of the spectrum is the social cost function that follows expected value rather closely. This approach is taken by the US Public Health Service in decisions regarding their budget allocations. In this case the goal is to minimize disability days because the social cost is assumed directly proportional to the total number of days of disability.

A second type of social cost function results if an individual's value system is used. Perhaps this explains the charitable organizations that raise money for research to develop cures for multiple sclerosis or muscular dystrophy. In terms of disability days to society, these diseases are probably far less significant than the common cold. The catastrophic nature of the effects upon the individual results in a personal evaluation of a very high social cost.

One way to represent the difference between the two systems is to assume that personal value systems charge an increasing social cost to each successive disability day. As an example of this proposed representation of the personal value system, the social cost of one individual being disabled for a year is greater than the cost of 365 separate individuals each sick for one day. An example of such a representation would be

$$\text{total social cost} = NC_1(1+i)^t, \qquad 1.$$

where N is the number of individuals involved, i is a daily interest rate, t is the time in consecutive days of disability, and C_1 is the personal cost of one disability day. If such a representation is used, the curve in Figure 4 is obtained.

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The mix of personal and societal cost scales selected is dependent upon the decision-making agency. Autocratic countries and military organizations are more likely to use a societal scale because for these agencies the general welfare of society is placed above that of an individual. Democratic governments are more likely to use a mix of both scales; the congressional decision to spend extensively for cancer research is probably a result of a personal value system.

The choice of a cost system will, in some cases, determine whether an option with a high probability of a few fatalities is preferable to an option with a lower probability of a greater number of fatalities. While there are compelling arguments for both systems, the choice can only be made by a reading of the public's preference.

The term *value of life* appears frequently in the risk-benefit literature, and the meaning is derived in a variety of ways (5). The original approach was to discount future earnings at an appropriate rate, to arrive at some value. Such a method has obvious drawbacks, for the life value of retired persons goes quickly to zero as does the value for those who work without direct compensation (e.g. housewives). Court awards for accidental deaths are not representative, for the compensation to an individual's survivors is probably representative of lost earnings. The approach taken by Sagan (6) is to charge a flat rate ($50) per day of disability and to use the National Safety Council equivalent of 6000 disability days for a death, which gives a life value of $300,000. This is a valid method if the societal value system is used, but it would not work for the personal system. A method

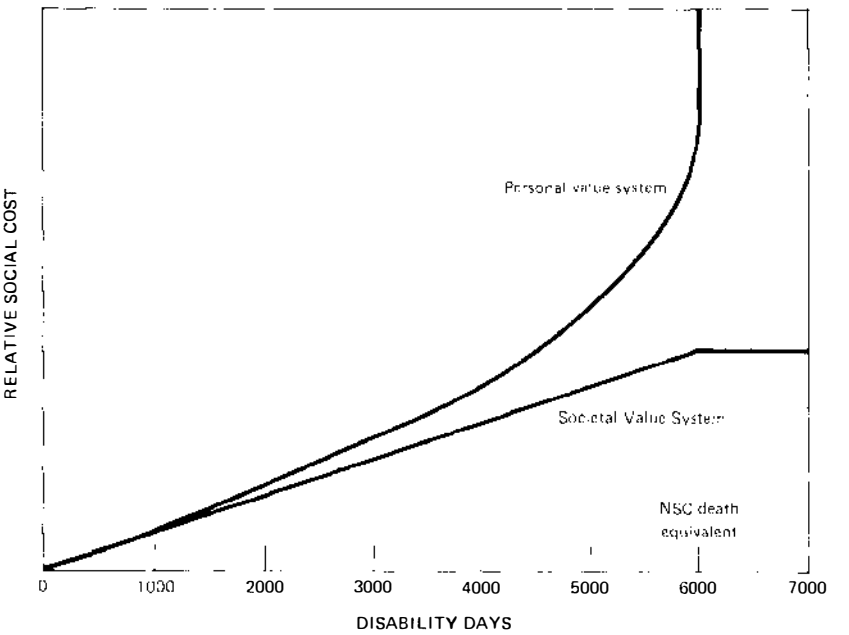

Figure 4 Value systems for social costs of disability.

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frequently employed is called *self-evaluation.* In this case, the premiums paid to workers in hazardous occupations are compared with the increased risk, and the marginal risk-benefit trade-off for an individual is scaled upward to a life value. Implicit in such a calculation is the assumption that the individual knows the level of risk and that employment in a similar but safer occupation is available at a slightly lower wage. In addition, the increase in risk must be small, or nonlinear effects (risk aversion) will occur. In general, the value of life remains a loosely defined term; the social values for risk should be more clearly defined before such a definition is made.

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Comparison of Risk and Benefit

It is rare to find a technology that provides a new benefit. The high-technology energy and transportation systems frequently used as examples in risk-benefit studies are always competitive with other energy and transportation technologies. When a new technology arises—for example, a medical treatment for a previously incurable condition—the risk-benefit analysis weighs the social cost against the benefits to gain insight into the criteria for acceptability.

A more common procedure is to compare several technologies through a risk-benefit viewpoint. In an analysis of the risks associated with nuclear power, it is more common to weigh these risks with the social costs of using coal or oil than to balance risks and benefits. The reason for this is simple. Coal and oil have been acceptable fuels for power plants for years. If the social costs of nuclear power compare favorably with those of coal and oil, then nuclear power automatically satisfies the risk-benefit criteria. Under these circumstances, the concept of benefit remains simple: the benefit is expressed in terms of electrical energy. Such a situation proves enormously helpful in an assessment of an energy technology because no widely accepted method of assessing benefits exists.

The typical problems of assessing benefits of energy, and electrical energy in particular, stem from the fact that prices are set according to costs, and a free market condition does not apply (7). Attempts to improve the benefit-assessment methodology frequently include additional benefits such as tax revenues and local employment, but these techniques usually represent double accounting. An alternative method from classical welfare economics is to use the concept of the consumer surplus, but such a method produces severe measurement difficulties. Fortunately, an assessment of benefits is not necessary for the general analysis of energy technologies. The historical record of energy usage provides proof of the acceptability of the technologies associated with the use of fossil fuels to generate power, with the possible exception of strip mining. If the total social costs of new energy technologies are lower than the social costs associated with the traditional production methods, then societal acceptability has been demonstrated.

A method commonly employed in comparison of energy technologies is predicting the health costs from various types of power plants with the assumption that each plant is of a given power rating and the plants are sited at equivalent locations. In this case the benefits are truly identical: the generation of power to serve the needs of a given population. The quantification of social costs may be

simplified under these circumstances, since all social costs need not be translated into a dollar amount. Instead, each technology is responsible for various types of health effects, which may be expressed in more convenient units such as injuries, fatalities, disability days, or years of life shortening. Due to the societal distinction between voluntary and involuntary risk, the analyses are frequently divided into occupational and public health effects. A risk-benefit analysis includes all the social costs associated with a given technology. In the electrical power field, this generally includes all health costs associated with the mining, transport, and preparation of fuel, combustion of fuel, and waste disposal. The combustion of fuel includes effects from both normal operations and potential accidents. In addition, an analysis of nuclear power requires the consideration of fuel reprocessing. The one health cost generally not considered in the analysis is the effect of the use of electricity, namely electrocution and electrically caused fires, because this is independent of the method of generation. Additional social costs include burdens on the environment and most frequently are expressed in terms of land-use requirements and quantities of pollutants emitted.

The methodology of assessing social costs due to environmental burdens is less developed than the comparative health cost methods. The reason for this is that the environmental burdens are of an aesthetic nature, whereas health costs may usually be translated into medical costs, days of disability, and fatalities. For this reason, risk-benefit studies have focused upon the health effects associated with the production of power, with less detailed comments offered regarding the environmental burden.

An even more difficult externality to quantify in the energy field is the potential social cost of undependable supplies of a particular form of energy. The current emphasis applied to reducing oil imports and establishing a goal of energy self-sufficiency indicates that this externality is now recognized. On a smaller scale, some industries are now switching from natural gas to electricity, due to the threat of nonavailability. An example of this is the glass industry, which is now building electric furnaces for glass manufacturing. Reliability of fuel supply is a significant factor in electric utility planning, although cost is also a major factor.

Interpreters of Risk-Benefit Analysis

The roles of the various participants in a risk-benefit decision process depend largely upon the societal structure. It seems that the scientist's role includes those activities up to and including the quantification of impacts, regardless of the decision-making process (see Figure 3).

In an autocratic society, the social costs of accidents are assumed directly proportional to the estimated expected values of direct accident costs. In this case, a social value system relating to risk characteristics (shown as *worth of alternatives* on Figure 3) is not applied, and the decision process is rather automatic. The risk assessor may in fact be the decision-maker.

In more egalitarian societies, the scientist's role ends with the quantification of impacts. The worth of alternatives has generally been added to the decision process by special-interest groups, letters to decision-makers, editorials by opinion-makers,

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and other inputs of political measure to the decision-maker. The degree to which the decision-maker (in this case, an elected official) accurately interprets and responds to the political input determines, to some degree, the success of the decision-maker. Two ways exist in which such a process can result in decisions inconsistent with societal values and scientific assessments. First, the input to the decision-maker may not accurately reflect the overall social values of the public. Second, the input is usually expressed as a recommendation, either pro or con, for a particular alternative of the decision process. In this case the input may reflect a faulty perception of the situation, rather than an accurate expression of values.

The issues are clouded because some degree of scientific disagreement exists about virtually every controversial topic. To provide a measure of consistency, the risk-assessor or members of the public can do several things. First, the assessor can indicate that certain courses of action are more consistent with prior societal behavior and, second, the character of the risk may be explored to indicate which risks are likely to be misperceived. Through the use of this information, the decision-maker can more accurately interpret the social values implicit in the political input. The goal of such a method is a separation of the debates over societal goals and scientific estimates.

Use of Risk-Benefit Analysis

Risk-benefit analysis can be applied in three principal areas. The first area relates to the allocation of resources for safety expenditures. In general, a law of diminishing returns applies to all types of controllable risk : risk reduction becomes progressively more expensive. If an accepted methodology for determining the social cost of risk is developed, safety allocations would be determined as demonstrated in Figure 5.

Ideally, safety expenditures should be made until the marginal exchange between social cost and control cost is equal; that is, the expenditure of one dollar for safety is expected to reduce the social cost by one dollar. This results in the most efficient allocation of resources available to reduce all risks.

The second area of application for risk-benefit analysis is in the setting of standards, whether for occupational safety or for public health risks. This will provide an analytic basis for trade-offs such as that between automotive emissions and mileage, and electric power plant emissions and electricity cost.

The final and most important application is in societal risk-taking decisions. Risk-benefit analysis provides a background of consistency through which decisions can be carefully examined. The consistency produced will ensure that the path of minimum social cost will be selected.

NATURE OF RISK

Before a methodology for dealing with risk on a societal level can be developed, it is first necessary to examine the nature of risk and the history of societal risk-taking. Each major element in such a process is described below.

Risk is defined here as the probability per unit time of the occurrence of a unit

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cost burden. The cost burden may be measured in terms of injuries (fatalities or days of disability) or other damage penalties (expenses incurred) or total social costs (including environmental intangibles). Risk thus involves the integrated combination of (*a*) the probability of occurrences, (*b*) the spectrum of event magnitudes, and (*c*) the spectrum of resultant personal injuries and related costs.

As thus defined, risk is directly related to the familiar insurance premium determination for any class of activity. Thus, automobile insurance premiums are based on the frequency of collisions, the distribution of their physical magnitude, and the distribution of the resultant damage. Better roads are addressed to the first point, elastic bumpers to the second, and seat belts to the third. This separation of parameters is often glossed over in many discussions of the subject, but it is important for analytic studies.

Characterization of Risk—Exposure Probabilities

The probability of exposure to risk (the first item above) has three major elements: space, population, and time dependency.

The spatial character of exposure probabilities can range from quite localized risks to global hazards. For example, the production and utilization of energy

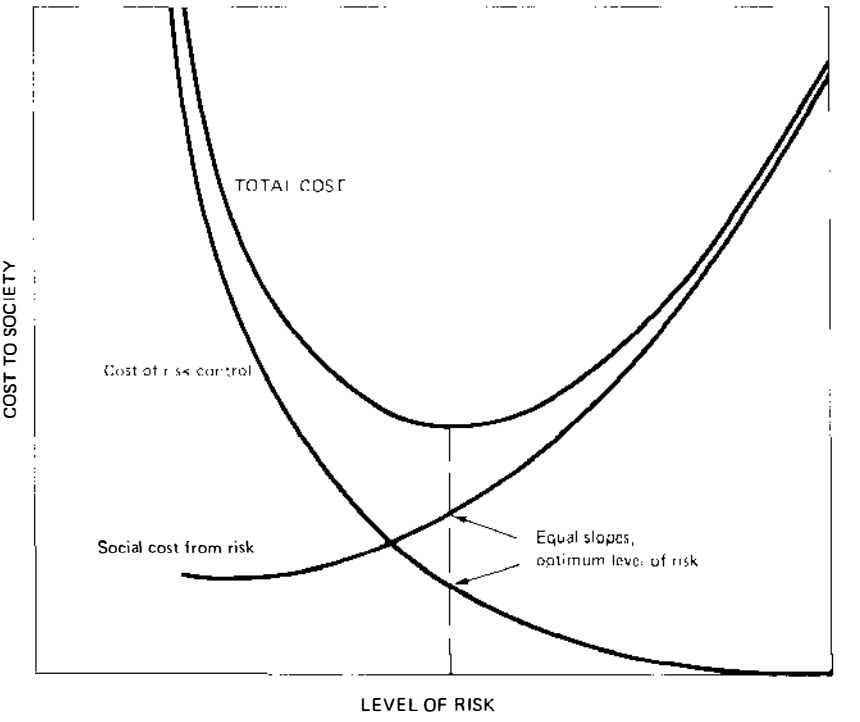

Figure 5 Social costs and control costs versus level of risk.

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causes effects over a wide range of space; hydroelectric dams and some pollutant emissions represent localized risks, whereas the production of carbon monoxide, the increase in global turbidity, and nuclear safeguards are of global concern.

A second aspect of exposure probability is determined by population dependency. For many types of risk, specific groups may be identified as the population fraction that bears a specific risk. While many such groups exist, certain group characteristics may be identified as the determinants of the risk-bearing population. The following list includes some types of group-dependent risks:

1. heredity—genetic diseases;
2. age—childhood or geriatric diseases, certain accident probabilities that are higher for certain age groups, such as poisons (children) and falls (older persons);
3. occupation—pneumoconiosis (black lung disease) among coal miners, burns to fire fighters, and many other occupational hazards;
4. sex—incidence of heart attacks in males, risk to women in childbirth;
5. activity groups—smokers, skiers, and gun owners.

The time-dependent exposure probability may be classed into three major groups:

1. continuous—describes most diseases and accidents that can occur any time;
2. periodic—certain risks that are periodic in nature such as hurricanes, tornadoes, influenza, and some earthquakes;
3. cumulative—the exposure probability of risk that is in some cases related to previous exposure such as smoking, pneumoconiosis, asbestosis, and radiation effects.

Magnitude and Impact of Events

The magnitude of a risk event is a physical measure and does not consider the consequences of an event to individuals. In this sense, an event's magnitude is not directly a measure of risk, but rather one of event characteristics. Examples of such measures are magnitude of an earthquake, height of a flood, or energy release from an explosion.

Impacts measure the effects of risk events upon exposed populations. As such, the impact is one key part of risk (the other is probability). This distinction between magnitude and impact is made because estimates of risk (probability of a specified impact) are frequently derived from a combination of two estimates: probability of an event of a given magnitude and the impact of an event versus magnitude. The relationship between magnitude and impact is explored in the next section under rare events and risk.

HYPOTHESIZED LAWS OF RISK

Risk has certain usually repeatable characteristics, which may be termed laws of risk. An exploration of these characteristics is useful for the purpose of comparing risks from different sources.

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Logarithmic Relationship between Probability and Magnitude

Risk is properly defined as the probability per unit time of a unit cost burden (injury) occurring. It consists of both the probability that some event will occur and the magnitude of damage that results if the event occurs. From data for various types of risk (see Figures 6 and 7) it is clear that the probability and magnitude are not independent but that for many risks the high-impact events are much less common than the lower-impact events. This result is in itself not surprising where societal choice existed, for it seems clear that in response to both natural and man-made hazards, successful societies have selectively evolved in a manner designed to avoid catastrophic events. What is surprising is that even for natural phenomena (earthquakes) the probability, or frequency, of the event usually falls off at least as fast as an exponential function of the magnitude for many types of risks (see Figures 8 and 9). Mathematically, this is

$$\log f = a - bm, \qquad 2.$$

where f is the frequency, m the magnitude, and a and b are constants.

If estimates of the probability of high-magnitude events are desired, the data base is usually sparse because the events are rare. The probability distribution for the general type of risk can, however, be estimated from the available data for less extreme cases. A class of statistical distributions, known as asymptotic distributions, have proven useful in estimating extreme probabilities for natural hazards such as floods and earthquakes. The asymptotic distributions come from the theory of extreme value distributions (9) and are useful because less restrictive conditions are required for the use of the asymptotic distributions than for the exact distributions of the extremes of functions (10). Extreme value distributions deal with the distribution of the maximum or minimum values in large samples of independent values drawn from an initial distribution. This approach requires knowledge of the initial distribution and the sample size.

The asymptotic-type distributions do not require as detailed information; the sample need only to be large and the initial distribution must satisfy more general requirements. $F(x)$ is the probability that some random variable is less than x (the cumulative distribution). If $F(x)$ tends to unity at least as fast as an exponential as $x \to \infty$, then the maximum values of large samples of independent events follow the Type I asymptotic distribution of maximum values. This condition is satisfied if the initial distribution is gamma, exponential, chi-square, normal, or lognormal, among others. The Type I asymptotic distribution for maximum values is

$$F(x) = \exp\left[-e^{-a(x-b)}\right]. \qquad 3.$$

From this it can easily be shown that

$$f(x) = a\exp\left[-a(x-b) - e^{-a(x-b)}\right], \qquad 4.$$

which reduces asymptotically to

$$f(x) = ae^{-a(x-b)}, \qquad 5.$$

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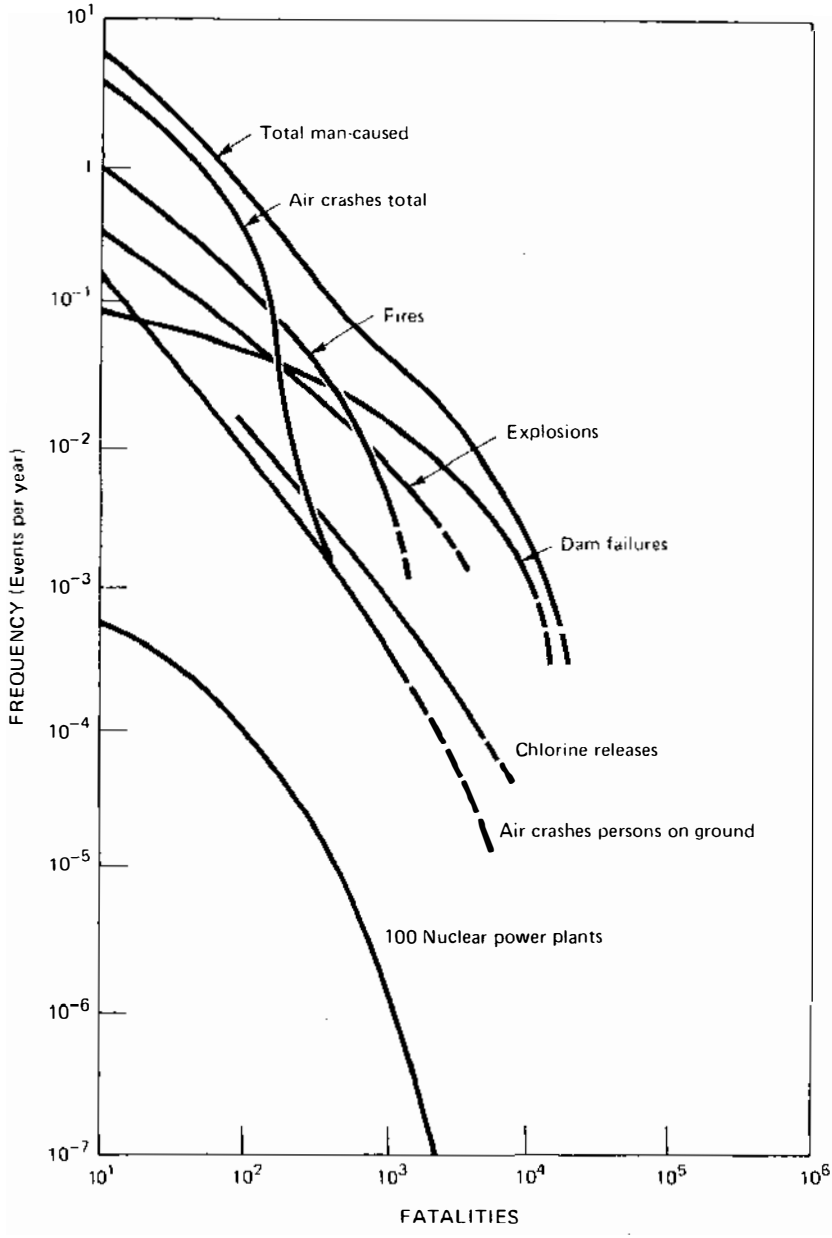

Figure 6 Frequency of fatalities due to man-caused events. Source: (8).

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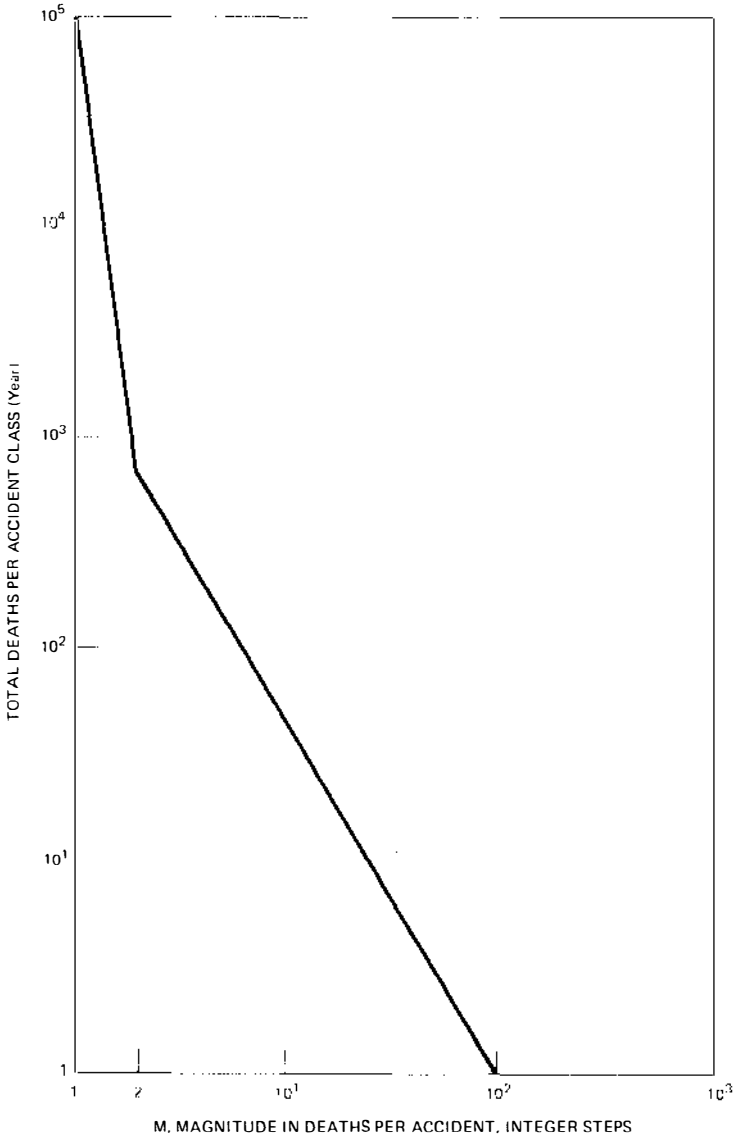

Figure 7 Total deaths arising from accidents that kill M people versus magnitude.

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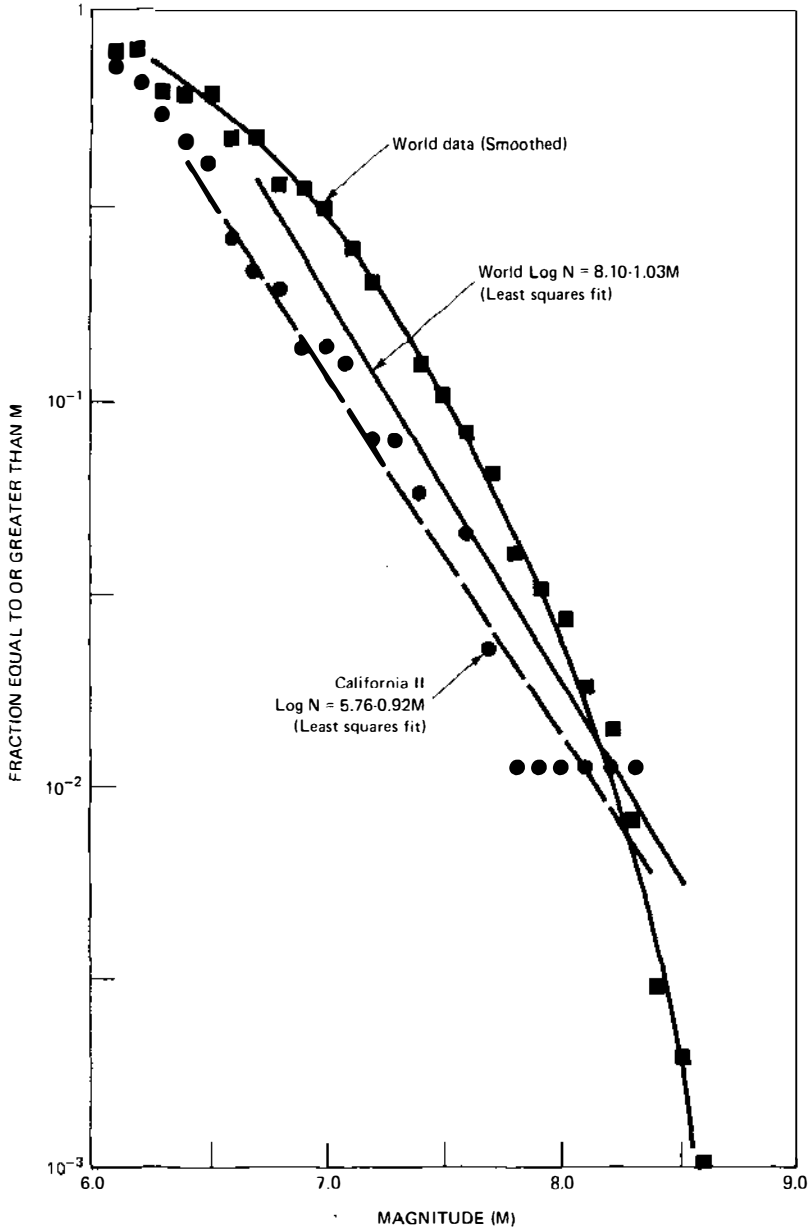

Figure 8 Magnitude distribution of shallow earthquakes 1904–1952.

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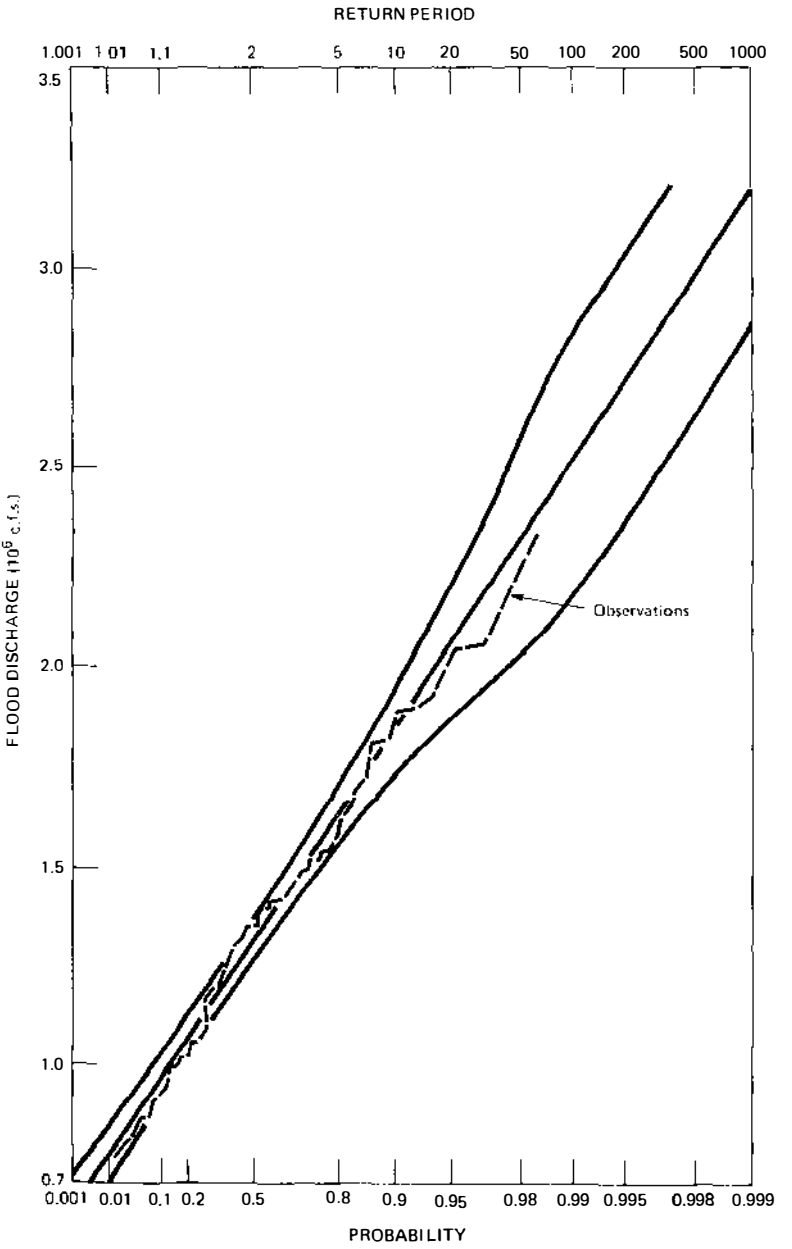

Figure 9 Mississippi River floods, Vicksburg, Mississippi, 1898–1949. Source: (9).

similar to equation 2. The return period for rare events is defined as

$$T(x) = \frac{1}{1-F(x)}, \qquad 6.$$

and asymptotically it converges to

$$T(x) = e^{a(x-b)}. \qquad 7.$$

If, as an example, large earthquakes of magnitude m are considered, the common notation is (10)

$$F(m) = \exp[-\alpha e^{-bm}], \qquad 8.$$

which can be written in Type I asymptotic form as

$$F(m) = \exp\left\{-\exp\left[-b\left(m - \frac{\ln \alpha}{b}\right)\right]\right\}, \qquad 9.$$

so the return period is

$$T(m) = \frac{1}{\alpha} e^{bm} \text{ (years)}, \qquad 10.$$

which means that it takes an average of $T(m)$ years to observe an earthquake of magnitude m.

This type of distribution is frequently applied to floods (9, 10), and the nature of the result may be seen from Figure 9.

A general list of natural hazard distributions has been compiled (11) (see Table 1)

Table 1 Examples of natural phenomena described by probability distributions[a]

Poisson Distribution

1. Meteorite strikes on (potential) human targets (12)

Negative Binomial

1. Frequency of tornadoes (13)

Gamma Distribution

1. Sea waves: height (14)
2. River levels: recurrence of levels being exceeded (15)
3. Precipitation: drought occurrence (16)

Exponential Distribution

1. River levels (15)

Rayleigh and Weibull Distribution

1. Wind speed (17)
2. Wave heights: trough-to-crest (14)

Lognormal Distribution

1. Tsunamis (18)
2. Hydrologic series (various examples) (19)
3. Tornadoes: dimension of damage swath (13)
4. Flood damage magnitude: USA (20)
5. Earthquakes: magnitude and frequency (21)

[a] Source: (10).

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and demonstrates that most natural hazards do satisfy the conditions necessary to be of the Type I asymptotic form.

Rare Events and Risk

An estimation of risk from rare events entails three steps. First, the probability of an event of given physical magnitude must be estimated, as described above. Second, the manner in which such an occurrence can produce injuries or fatalities must be developed, and finally the population distribution in the vicinity of an occurrence must be known. In general, the population distribution is easily measured or estimated; estimates of injuries from an event are more difficult to perform.

All rare events of this type have one common feature, the release of energy. To translate this into an estimate of risk, two mechanisms must be quantified: the nature of energy transport through the population and the relation between energy exposure and injury. These mechanisms may be either probabilistic or deterministic, and it does not seem that either mechanism is capable of being described in a general sense for a large class of risks. As examples of energy transport mechanisms, several hazards may be considered. Earthquake and explosion energies are best described deterministically; earthquake propagations can be estimated from measurable soil characteristics, and explosions transmit energy that varies with the inverse of the square of the distance, to a first-order approximation. A man-made hazard that also produces an energy release that propagates in a deterministic method is a flood due to a dam failure. In this case, the flood plain may be predicted.

Probabilistic transport mechanisms apply for estimates of hazard from events such as forest fires and nuclear power plant accidents, because in both cases the energy transport is strongly dependent upon the wind direction and speed, where the wind can only be characterized in a probabalistic sense. In any case, a general rule is that individual energy exposures are proportional to the total energy release.

The relationship between individual energy exposure and the degree of injury is frequently more difficult to quantify but does have some general characteristics. For many types of hazards, two thresholds may be defined. The first threshold places a lower bound on certain energy exposures; this level cannot produce injuries. Mechanistically, this lower bound corresponds to exposures to which the body responds elastically. The upper threshold defines a level of individual energy exposure that will cause death, if physical injuries are considered, or complete destruction in the case of property damage.

To consider the meaning of these thresholds, an example of an airplane accident may be used. In a crash, the individual energy exposures in general are in excess of the upper threshold, and thus death is the most likely result. A bump caused by slight turbulence or a rough landing rarely exceeds the lower threshold, and no injuries result.

For those exposures in which the two thresholds are quite close in value (such as the effects of electric shock or drowning) the body is said to be quite resilient. This implies that recovery from a nonlethal level of energy is usually rapid. The response to other damage mechanisms, such as mechanical injury, is one of lesser resilience.

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Between these two thresholds, the damage is a monotonic function of energy, although frequently in a probabilistic sense.

An example of a single mechanistic model of the damage due to a localized

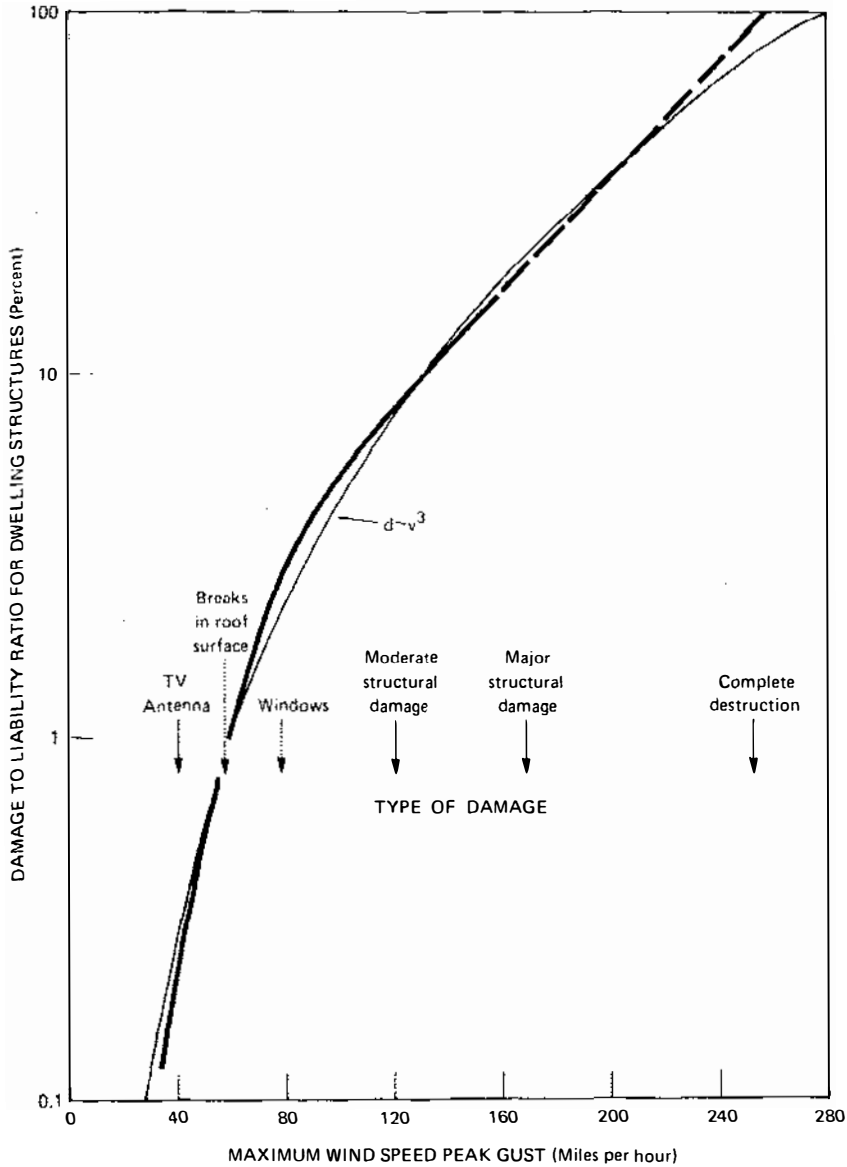

Figure 10 Dwelling damage versus wind speed relationships. Source: (23) except for $d \approx v^3$ curve.

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energy exposure can be postulated for the property damage due to wind gusts. In this case, the damage is assumed to vary as the cube of the velocity, because that is the rate at which wind transmits energy to structures. This model is in excellent agreement with experimental evidence (22, 23) (see Figure 10). In the case of wind, the upper damage threshold occurs at approximately 250–280 mph.

While a general response to hazards cannot be found, the empirical evidence is that the damage resulting from a range of event magnitudes also varies as the log of the frequency (see Figures 6, 7, and 11). From this empirical evidence, it is possible to construct a single, three-dimensional surface for the number of accidents, A, as a function of d disability days lost per person and n people injured per accident (see Figure 12). Because the data are difficult to obtain, Figure 12 is only an approximate representation of the actual surface. The surface is defined by

$$A(n, d) = \frac{a}{n^b d^c}, \qquad 11.$$

where a, b, and c are constants.

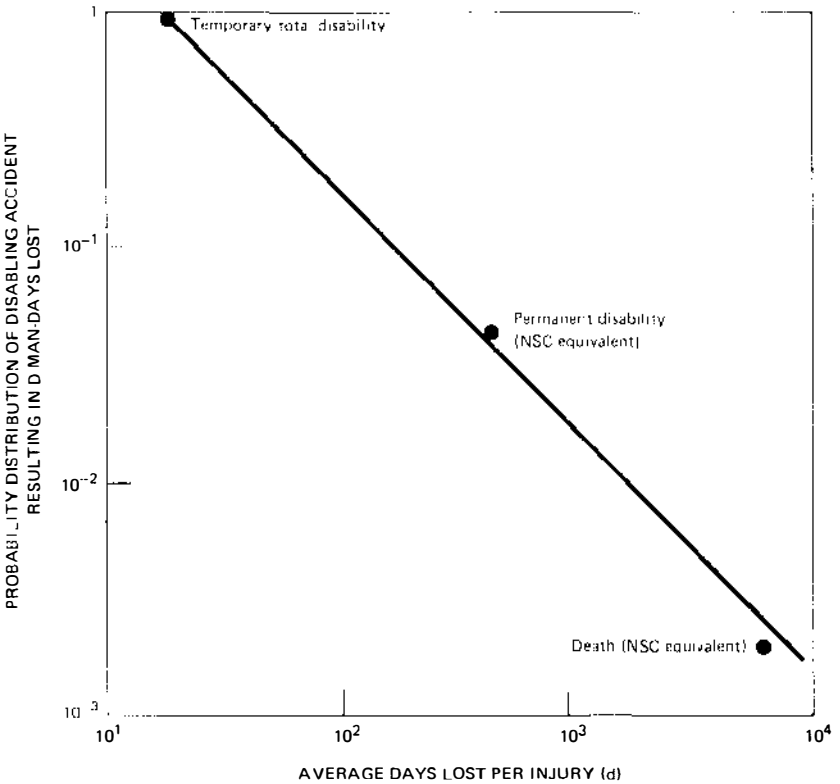

Figure 11 Probability distribution of disabling and fatal accidents versus average days lost (US manufacturing industries, 1969).

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In Figure 12, $A(n,d)$ represents all US accidents, a is 8×10^6, b is between 1.5 and 3 (depending upon whether $n = 1$ is included), and c is between $\frac{1}{2}$ and 1. Such a surface may be defined for any risk, and in many cases the coefficients b and c

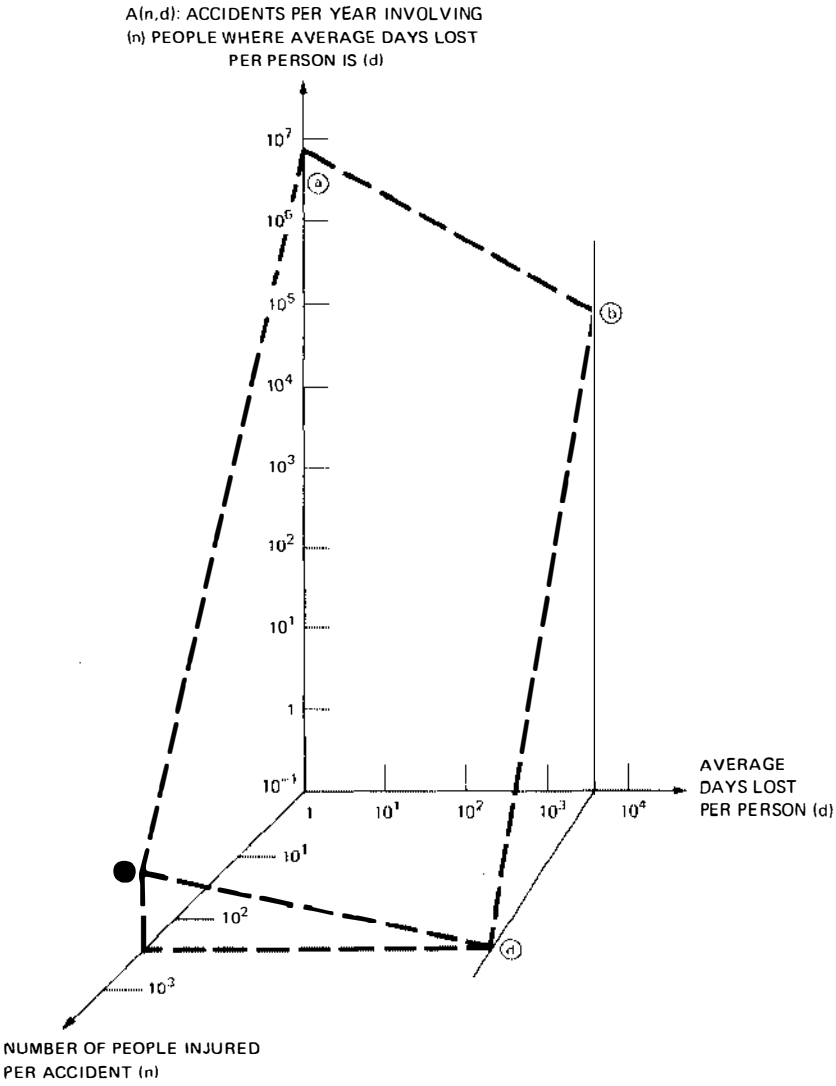

Figure 12 Distribution of fatal and disabling injuries by magnitude and severity. ⓐ Single injury per accident (1 day disability); ⓑ single fatality per accident (6000 day equivalent); ⓒ maximum group per accident with 1 day average disability; ⓓ maximum fatalities per accident.

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appear to be similar. Some rather special cases may be considered that fit the general form of the relation, although the constants will be quite different from those for average risks. Two examples mentioned previously are drowning and electrocution, which would be expected to have a very high value for c. This is due to the nature of these risks in which the damage thresholds are quite close. To this end, c is a measure of the individual resiliency to a risk. The constant b (related to the number of people involved per accident) will vary with the distribution characteristics of the population. In the case of aircraft accidents, the population density is quite high at the point of energy release, which would suggest a higher value for b. The usefulness of such a surface is indicated for those risks resulting in a distribution similar to that for all accidents: a great deal of information can be inferred from a slight bit of statistical information. From a societal point of view, the total number of disability days T (and hence the social cost) resulting from a particular risk is simply the volume integral of the surface:

$$T = \int_1^{\infty} \left[\int_{d_1}^{d_2} A(n, d)\, dd \right] dn, \qquad 12.$$

where d_1 and d_2 are the damage thresholds previously defined.

In the case of US accidents, d_1, the lower threshold for damage, would be one disability day (accidents resulting in no disability days do not contribute to the total social cost). The National Safety Council equivalent of 6000 disability days per death can be used for d_2. For $b > 1$, and $0 > c > 1$, the total number of disability days is

$$T = \frac{a(d_2^{1-c} - D_1^{1-c})}{(b-1)(1-c)}. \qquad 13.$$

From this result, and the estimates for a, b, and c given previously, it is quite evident that the most significant contributions to total disability came from accidents involving only one individual. It should be noted that T is a measure of social cost in disability days and is not representative of personal value systems.

Uncertainty Principle

One major factor in the acceptance and perception of risk is the degree of uncertainty associated with the probability estimates, particularly of future hypothesized situations, discussed earlier in the section on perception of risk. It is valuable to examine the sources and nature of the uncertainty in a quantitative manner to put the discussion of perception in perspective.

Accident probability estimates for complex systems are usually made by estimating the failure probabilities of individual components of the total system, then combining the probabilities of the various failure modes by use of fault trees or event trees into an overall probability estimate. Uncertainty arises from two sources in such an estimate. The first source is that due to statistical variations in the failure probabilities of the individual components, and it results simply because the assessor is limited to a finite number of experiments (or the operating histories of the components is finite). Such uncertainty is reducible by increased experimentation, although the

cost associated with producing more precise estimates is frequently considered excessive. This type of uncertainty is referred to as *experimental uncertainty*.

The second source of uncertainty seems more significant in its influence in risk perception. This uncertainty is due to modes of failure not previously considered. These failures have been termed *hypothetical* (24), for they are events that have not been observed. The hypothetical uncertainty is due to the possibility of unanticipated occurrences. While the uncertainty resulting from the possibility of unanticipated events is not removable, some justification can be provided for the engineering judgment that the unanticipated event risk is not expected to be high.

In both cases, a simple relationship may be developed to reveal the characteristics of the uncertainty as they relate the probability estimate to operating experience (which in the first case is equivalent to the number of experiments and in the second case is related to the cumulative operating time). If U_a represents experimental uncertainty, U_n hypothetical uncertainty, P the assessed probability, N_1 the number of experiments that have been run (assumed proportional to the investment I), and N_2 a relative measure of societal experience with a particular system, then the relationship is

$$U_a \approx \left(\frac{1}{PN_1}\right)^{1/2} \approx \left[\frac{1}{(PI)}\right]^{1/2}, \tag{14.}$$

$$U_n \approx \frac{1}{PN_2}, \tag{15.}$$

and thus the total,

$$U = \frac{a_1}{(PN_1)^{1/2}} + \frac{a_2}{PN_2} \tag{16.}$$

The full derivation of these results is in the Appendix. This indicates that two types of experiments give information to reduce uncertainty. The first type, N_1, carries a cost that increases with decreasing probability of an accident. The second type of experiment, N_2, is a free by-product of normal operating experience.

The second relation, that for unanticipated uncertainty, perhaps lends some credence to the intuitive statement of an experienced engineer who claims to be "confident that everything of significance has been considered." While this is not always true (the designer of the Boeing 727 certainly never considered the possibility of a hijacker parachuting from the rear door), an upper bound on the probability of these new events does exist.

While it would be foolish for anyone to claim omniscience in any new technical field, nevertheless there is a professional basis for believing that the estimates of end-event probability are reasonably correct, i.e. within a few orders of magnitude either way. This is because the event-tree analyses indicate that while there may be many initiating circumstances, there are a limited number of key effects, that is, few outposts result from the event sequence with many inputs. As an extreme example, the most serious public hazard from a nuclear power plant would be an extensive sequence resulting in large amounts of radioactive emissions to the

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atmosphere. For this to occur, a substantial fraction of the radioactivity contained in the nuclear core would have to be released. We do know that the only way this can happen physically is by a melting of the core fuel. Thus, the core melting becomes a key point that all initiating circumstances would have to reach before significant public hazard could occur. Thus, even if there are some unknown failure modes that might eventually lead to a core meltdown, that particular phenomenon acts as a common output for many such event sequences. Thus, if the nuclear power plant is designed to handle such an end-point event as a core meltdown, the existence of a few unknown sequences presumably will not alter significantly the public hazard probabilities.

The validity of this assumption depends on the ratio of unknown to known failure modes of "like kind." For example, if the unknown are roughly equal in number and of roughly the same importance as the known, then the actual probability of an end effect would be twice that calculated from the known event tree. Because of the uncertainties in the probabilities of failure of an individual component or subsystem, the final end-effect probability in a nuclear system calculated from known event trees is likely to be uncertain to at least one order of magnitude. Thus, an estimated end-release probability of 10^{-7} (one in ten million per year) may actually be 10 times lower or higher. Therefore, a missed failure mode is not important unless it is differs radically from any considered in the design and also effectively bypasses many of the plant protective systems. Clearly, some experience with, and insight into, plant operating experience and failures is necessary to provide the designer with a reasonable base for event-tree probability analysis.

Resilience

The concept of resilience to a particular event's impact was introduced briefly in earlier sections, in particular in the discussion of the elasticity of individuals to the hazards of drowning or electrocution. This concept can be expanded to the societal level to consider those events capable of causing a lasting social impact.

Two principle types of societal resilience should be examined, relative to two different types of damage. First is the accident such as an earthquake or flood that causes a great deal of immediate damage. The threat associated with this type of event is that the loss of substantial portions of a population and resources will require a substantial effort and time for recovery. The second type of risk to a society is that which threatens the societal structure and culture, rather than large losses of life. This second type of risk and its relations to societal resilience is of great importance, for large-scale physical disasters have been routinely tolerated by societies for years, and populations continue to live in areas of high risk from flooding or earthquakes.

The importance of the resilience factor is the apparent nonlinearity of societal response to accidents as the impacts increase. The following quotation (25) perhaps dramatizes the issue:

> Small accidents throughout the world kill about 2 million people each year, or 4 billion people in 2000 years. This is "acceptable" in the sense that society will

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> continue to exist, since births continually replace the deaths. But if a single accident were to kill 4 billion people, that is, the population of the whole world, society could not recover. This would be unacceptable even if it only happened once in 2000 years.

The concept of resilience deals primarily with the survivors' point of view, unlike individual risk acceptance.

An example of the risk to societal stability is war, in which the loser suffers a dramatic change in structure and culture, as in the South following the US Civil War. A more localized threat would be the case of increasing water pollution in an area where the predominant industry is fishing, as has happened with mercury in some areas of Japan. The key factor in both of these cases is the long time required for cultural recovery. In the production of electricity, this is probably a key factor in the perception of risk from nuclear power plants. While a number of studies have indicated that the risk of nuclear power is lower than that of fossil-fueled electric power of hydroelectric power, the time frames associated with waste management and the fear of long-term contamination represent a type of risk different from a dam collapse or oil tanker explosion. While these risks have been exaggerated in many instances, the nature of this type of risk is subject to a set of social values different from the more direct threats. This is perhaps the reason for increasing concern over acid rainfall and trace metal contamination resulting from the combustion of coal. As a further example, a prolonged energy shortage could produce a severe economic impact, resulting in substantial social changes. It is for this reason that the factors of societal resilience need to be considered in national planning.

This study of societal resilience is an approach to the evaluation of the elasticity of a society to high-impact events and to the identification of those characteristics of societies that determine such resilience. One such factor is the level of technological development of the society. The more technically advanced a society is, the lower its resilience. This is due to a complex societal infrastructure that cannot operate with a sizable portion of its subsystems missing. In less developed areas, with less division of labor, the culture is more immune to accidents. An example of the lesser resilience of technological cultures may be seen from the bombing of ball bearing factories in Germany in World War II. While the ball bearing industry was small in comparison to the total industrial capability, the infrastructure was such that the loss of ball bearings would have been a substantial blow to the society at that time. Conversely, the severe flooding that caused over a hundred thousand fatalities in Bangladesh was not a major test of societal resilience because the social structure is dependent only upon the quantity of food produced, not upon vital industries or key population segments. In such a case, the population recovers rapidly to a level constrained only by the food supply. A striking example of the sensitivity of the US economy occurred with the oil embargo of 1973–1974, and the effects were far reaching even though the imported oil represented only a small portion of the total economic expenditure of the United States.

The key factors that seem to determine the societal resilience to a given accident or event may be arranged in the following dimensional form; if the

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resilience is denoted as R, it follows that

$$R = \frac{PL}{B(T)S^a t_r^b t_d^e M^f t_c^g} \qquad 17.$$

seems reasonable. In this relation, P is the societal population, L its average lifetime, B a monotonically increasing function of the level of technology T, S the size of population affected by the event, t_r the average recovery time for an injured population group, t_d the time to discover the source of damage, t_c the time to correct the situation, and M the average disability per person affected. The factors a, b, e, f, and g are constants. Although there are unquestionably other significant factors, this relationship may provide a starting point for work on the subject of societal resilience. Ecologists have studied a similar problem, that of species resilience (26). The topic of resilience as it relates to a societal value system for risk is explored in the discussion of that topic. It should be recognized that this relationship is quite crude and serves more as an example than as a proposed societal model.

The impact of considerations of resilience upon the societal value system for risk has not been explored in any detail, although a suggestion has been made by Wilson (27) to estimate the social costs of accidents of n fatalities as proportional to n^2 rather than n. An additional factor for involuntary risk is referred to as the "cost of public confidence."

Some inference can be drawn from empirical risk data for the social values appropriate to high-impact events. If f_n represents the frequency of accidents in which n lives are lost, it follows that

$$f_n = \frac{\alpha}{n^b}, \qquad 18.$$

as demonstrated in a previous section. Typical values of b lie between 1.5 and 3.0. If one were to make the common overt assumption that all lives lost in accidents are of equal value, then the social cost due to the risk of an accident with magnitude n is

$$f_n nl = \frac{\alpha l}{n^{b-1}} = \frac{\text{const}}{n^{b-1}}, \qquad 19.$$

where l is the societal value of each lost life. The conclusion that must be drawn from the assumption that all fatalities are of equal cost is that the high-frequency, low-magnitude accidents are of greatest social cost because the observed values of b are greater than unity.

An analytic interpretation of the empirical data supports the assumption that for fatalities resulting from any technical system, the relationship between accident frequencies and number killed has been adjusted by investment in safety so that each frequency point has social value equal to any other, i.e.

$$f_n nl_n = \text{const}, \qquad 20.$$

in which l_n represents the societal value of each life lost in an accident of n

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fatalities. From equation 20 is derived

$$f_n n l_n = \frac{a l_n}{n^{b-1}} = \text{const} \qquad 21.$$

and

$$\frac{l_n}{l_1} = n^{b-1}. \qquad 22.$$

The conclusion resulting from such an assumption is that each additional life lost in an accident is increasingly more costly to society. The cost of an accident of n fatalities is then

$$f_n n l_n = f_n n^b l_1. \qquad 23.$$

For the case $b = 2$, this corresponds directly to Wilson's result (27).

Objectives of Risk Analysis—Identification

Three methods are employed to identify risk : empirical evidence, statistical inference, and postulation based upon a transfer of experience or the laws of nature. Risk identification through empirical or statistical means is straightforward, but the third method is of more interest in the energy field because the types of risk associated with new or developing technologies are frequently postulated. This course is usually preferable because action may be taken before a statistically significant portion of the population is injured. In the energy area, the most widely studied risks are those from nuclear power. While no members of the public have been killed or injured by commercial nuclear plants, a number of possible risks have been identified and studied, by using a transfer of experience from radiation effects upon animals and from people exposed to radiation from sources other than power plants.

Risk Estimation

The estimation of risk contains both estimates of exposure probabilities and event impacts. These estimates generally require different skills. As an example in the energy field, the risk from accidents in light-water reactors is estimated by computing the probability of the release of a specified amount of radioactive material, estimating the subsequent exposure of a population to this material, and then estimating the health effects due to that level of exposure.

In this case, the first two estimates (release probability and subsequent exposure) are within the realm of the engineer or physical scientist. The estimate of health effects due to the postulated exposure is made by medical specialists, usually health physicists. For this case, the greatest uncertainties seem to lie within the estimates of the probabilities of release; the estimates of exposure due to a release and predicted effect of exposure are more generally accepted. The situation is quite opposite for the estimates of health effects due to the routine emissions of fossil-fueled power plants and automobiles. The exposure levels are directly measurable, but the health effects are not well known. The two roles—probability estimation and impact estimation—are not completely separable, for the probability varies with

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the postulated amount of impact. This relationship was previously explored under the first hypothesized law of risk, the logarithmic relationship between probability and impact.

Estimates can be developed in four ways. First, the analyst can apply the laws of nature directly, even though these laws may be empirically based. An example of this would be an estimate of the probability of failure of a component due to metal fatigue. Second, the estimates can be developed from historical or experimental data. This is generally the source of estimates for failure or accident rates of widely used devices such as pumps and relays, or for activities such as automotive travel, skiing, or coal mining. The third method is that of transfer of experience, where probabilities of failure are assumed similar to those of similar devices. The final method, systems modeling, is actually a combination of the previous methods and usually includes the estimation of accident trees. This last method provides estimates for complex technologies without established accident rates. Estimates of risk from nuclear reactors are made in this manner.

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CONCLUSION

Risk-benefit analysis is an increasingly important part of technology assessment. As the capability to estimate the external effects of technical systems improves, and as the ability to modify and reduce risk from these systems develops, a methodology to deal with questions such as "How safe is safe enough?" is needed to efficiently allocate societal resources.

Three principal areas of application of risk-benefit analysis have been identified. The most fundamental application concerns the societal choice of expanding or curtailing the development of our existing technological capabilities. For example, the relative emphasis on mass and individual transportation systems is such an issue. A second area for risk-benefit analysis is in setting performance targets for existing or new technologies where trade-offs between safety, environmental effects, and cost can produce major social and economic impacts—for example, air quality criteria. The third application involves decisions between competitive technical systems that produce a similar beneficial function but with differing societal costs. For example, the selection of either coal or uranium as a fuel system for a new electrical power plant must be based on a comparison of their social costs, since the same output of electricity would be generated by both.

A step-by-step procedure to deal adequately with such issues is not yet available. Rather than try to describe the various suggested methodologies in detail, we have reviewed the general philosophic features common to most risk-benefit decisions. In many cases we have deliberately simplified analytical descriptions of the important dimensions of risk, with the hope that this might seed future work in these areas.

APPENDIX: UNCERTAINTY PRINCIPLE

If experiments and analyses are applied to the assessment of a probability, uncertainty will accompany the assessment for two reasons. First, the usual sort of uncertainty due to a finite (rather than infinite) number of experiments will be present, and

second, a possibility exists that events will occur through mechanisms not considered in the analysis. What is usually of primary interest is an upper bound on the estimate of uncertainty, and attempts to estimate the difference between the assessed value and this upper bound refer to the bias in a system. The word *bias* unfortunately carries different connotations to the nonstatistician readers from the meaning of the word to statisticians. Because it is hoped that the reference to this topic will interest both groups, the word *uncertainty* is used and defined in a rather arbitrary manner. In addition, the derivation is not strictly rigorous but serves to demonstrate the functional form of the relationship.

If the assessed failure probability is termed P_a, the uncertainty U, and the true failure rate that would in theory be observed with unlimited operating experience P_t, it follows that

$$P_a(1+U) = P_t. \tag{A.1}$$

This definition was chosen because the uncertainty associated with low-probability events is frequently expressed as a product, e.g. the probability is P_a to within a factor of 20. The quantity $(1+U)$ was chosen so zero uncertainty would refer to $P_a = P_t$.

As mentioned above, the uncertainty arises from two sources. The first source, experimental uncertainty, is usually expressed as confidence limits for a number of standard deviations, σ, around the assessed probability. The second source is the probability of new events, termed P_n. For the upper bound, we find that

$$P_t = P_a + \alpha\sigma + P_n, \tag{A.2}$$

where α is a constant. From equation A.1 is derived

$$P_a(1+U) = P_a + \alpha\sigma + P_n \tag{A.3}$$

and

$$U = \frac{\alpha\sigma}{P_a} + \frac{P_n}{P_a} = U_a + U_n. \tag{A.4}$$

Uncertainty Principle for Experimental Testing

The value of U_a may be computed from the common method of defining confidence limits. In this case P^* is the upper bound threshold probability and $\Phi(y)$ is the cumulative probability of a normal distribution.

To compute the one-sided confidence limit, the cumulative distribution is

$$\Phi(y) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{y} \exp(-\tfrac{1}{2}x^2)\, dx. \tag{A.5}$$

The confidence is defined by

$$\frac{P^* - P}{\alpha} = y, \tag{A.6}$$

where the law of large numbers justifies the choice of a normal cumulative function. For a binomial process (experiments that result in either success or failure) the

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standard deviation for the estimated mean is

$$\sigma(P) = \left[\frac{P(1-P)}{n}\right]^{1/2} \quad \text{A.7}$$

where n is the number of tests.
For

$$P^* = (1+U_a)P, \quad \text{A.8}$$

we find that

$$\frac{(1+U_a)P - P}{\sigma} = y \quad \text{A.9}$$

or

$$U_a = \frac{y\sigma}{P}. \quad \text{A.10}$$

This is the same as the previous definition from equation A.4.

For this case we find that

$$U_a = \frac{y\left[\frac{P(1-P)}{n}\right]^{1/2}}{P}, \quad \text{A.11}$$

and for $P \ll 1$, this reduces to

$$U_a \approx \frac{1}{(Pn)^{1/2}}. \quad \text{A.12}$$

New-Event Uncertainty Principle

It is assumed that some probability of system failure can be due to the occurrence of a "new" event, that is, one for which statistics are not available and estimates of failure due to this event were not included in the assessment.

This situation is roughly similar to a series of experiments (in this case operating experience and transfer of experience) during which no failures were observed as a result of this particular cause. If this is considered in the framework of Baysian analysis, with a diffuse prior probability, then the probability distribution for such an event is

$$f(P_n) = (N+1)(1-P_n)^N, \quad \text{A.13}$$

where N represents the operating experience. If one considers events such as "giant meteor destroys earth," N is 4×10^9 years (the age of the earth). The expected value of the probability in this case is

$$E(P_n) = \frac{1}{N+2} \approx \frac{1}{N}. \quad \text{A.14}$$

As a result, the probability that a giant meteor will destroy the earth is expected to be 2.5×10^{-10}/year, if only the experimental evidence with the absence of such

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meteors is considered. This simplistic approach assumes that the probability of meteors has not changed over the last 4×10^9 years.

From the definition of new-event uncertainty (equation A.4) is derived

$$Un = \frac{P_n}{P_a} \approx \frac{1}{NP_a}. \qquad A.15$$

From the brief example it seems clear that risks or system failure probabilities of less than 2.5×10^{-10} are not really worth considering, as an unremovable risk threshold of 2.5×10^{-10} has been defined.

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